Hydroprene Prolongs Developmental Time and Increases Mortality of Indianmeal Moth (Lepidoptera: Pyralidae) Eggs

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ABSTRACT Eggs of the Indianmeal moth, *Plodia interpunctella* (Hübner), were exposed to the labeled rate of hydroprene (1.9×10^{-3} mg [AI]/cm^2) sprayed on concreted petri dishes. These eggs were exposed for 1, 3, 6, 12, and 18 h and until hatching (continuous exposure) at temperatures of 16, 20, 24, 28, and 32°C and 57% RH until the emergence of first instars. The developmental time and egg mortality were significantly influenced by temperature and exposure periods. At 16°C, hydroprene did not cause differences in developmental time when eggs were exposed for different periods. At temperatures >16°C, both exposure period and temperature influenced developmental time. The maximum developmental time (15.0 ± 0.2 d) occurred at 16°C, and the minimum developmental time (3.2 ± 0.3 d) occurred at 32°C. Mortality increased when eggs were exposed to hydroprene for longer periods at all of the five tested temperatures. The greatest mortality (81.6 ± 2.1%) occurred when eggs were continuously exposed on treated surfaces at 32°C. We used developmental time instead of rate (1/developmental time) to fit simple linear or polynomial regression models to the development data. Appropriate models for developmental time and mortality were chosen based upon lack-of-fit tests. The regression models can be used in predictive simulation models for the population dynamics of Indianmeal moth to aid in optimizing use of hydroprene for insect management.

KEY WORDS *Plodia interpunctella*, insect growth regulator, surface treatment, population dynamics

The Indianmeal moth, *Plodia interpunctella* (Hübner), is a cosmopolitan pest of raw stored commodities and of packaged and processed food (Cox and Bell 1991). Currently, management of Indianmeal moth often depends upon the use of conventional insecticides. Hydroprene, a juvenile hormone analog, is considered to be an alternative to conventional insecticides because of its specific activity against immature insect stages, low persistence in the environment, and nontoxic effects on mammals. Most early tests with hydroprene were conducted against stored-product beetles (Loschiavo 1975, McGregor and Kramer 1975, Amos et al. 1977, Rup and Chopra 1984, Shanthy et al. 1995). Hydroprene completely suppressed adult emergence of almond moth, *Cadra cautella* (Walker), formerly *Ephestia cautella* (Walker), when inshell peanuts were sprayed at 5 ppm (Nickle 1979). More recently, Arbogast et al. (2000) showed reduction of insect populations of several stored-product insects, including the Indianmeal moth, when hydroprene was applied as a surface spray treatment in a retail store.

There are several reports of the effects of hydroprene on the eggs of different lepidopteran field crop pests. However, most of these studies describe indirect effects of hydroprene on eggs developing within the adult female. Inhibition of egg maturation, variations in the compound egg chambers in the ovarioles, and sterility have been reported for croton caterpillar, *Achaea janata* (L.), exposed to hydroprene (Nair and Muraleedharan 1992). Hydroprene caused oocyte resorption in *Leptocoris coimbatorensis* Gross (Kaur et al. 1987). Chakravorty et al. (1989) showed abnormalities in the growth and differentiation of gonads and reduction in egg and sperm maturation in three lepidopteran species: rice moth, *Corcyra cephalonica* (Stainton); *Anomis sabulifera* (Guenée); and *Utethesia pulchella* (L.), when hydroprene was applied to the food of immature stages.

There is only one published study reporting the direct effects of hydroprene on the eggs of stored-product insects that are developing externally during the postovipositional period. Similar studies were conducted by administering hydroprene into the diet of insects or by topical application. The one applicable study, by Bhargava and Urs (1993), reported reduction in hatching percentage of eggs of rice moth, which were of different ages when treated, as a result of hydroprene application. Under natural storage circumstances in warehouses and retail environments,

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hydroprene is applied on the surface as either an aerosol or spray treatment, and there are no data regarding direct effects when the eggs are exposed on a treated surface. The objective of this study was to quantify the effect of hydroprene as a surface treatment on the eggs of Indianmeal moth, including the effects of temperature and exposure time on egg developmental time and mortality.

Materials and Methods

Experimental Design. The experiment was designed as a split-plot structure (Kuehl 2000), with incubators as the whole plot and concreted petri dishes as subplot experimental units. Five temperatures (16, 20, 24, 28, and 32°C) were randomly assigned to whole plots, and six exposure intervals (1, 3, 6, 12, and 18 h and a continuous exposure period) were randomly assigned to the subplots (30 treatment combinations of temperature and exposure intervals). The continuous exposure mimicked conditions that would normally occur when eggs were laid on a treated surface, and the timed exposure intervals were selected to quantify the effects of time as a dosage factor. Five incubators (ThermoForma, Marietta, OH), one for each temperature, were used in the study. Humidity chambers were created inside plastic containers (26 by 36.5 by 15 cm) with a waffle-type plastic grid in the bottom. A saturated NaBr solution was used to maintain 57% RH inside each plastic container (Greenspan 1977), and two containers were used for each incubator. We used 57% RH, which is approximately the same humidity found in many stored-product environments. Daily temperature and humidity inside the individual incubators were monitored by placing a HOBO (Onset Computer Corporation, Bourne, MA) inside the humidity containers. Humidity was uniform across all of the whole and subplot treatments and therefore was not considered as part of the treatment design.

Insects. Indianmeal moth eggs were obtained from a laboratory culture reared on a laboratory standard diet mixture of cracked wheat, wheat bran, wheat germ, honey, glycerin, yeast, sorbic acid, benzoic acid, and water. The laboratory strain is a mixture of several field-collected strains and has been maintained for ≈5–7 yr at the Grain Marketing and Production Research Center, Manhattan, KS. All cultures are held inside incubators set at 27°C and 60% RH. Indianmeal moth eggs were collected by placing 50 adult mating pairs in a 0.95-liter glass jar with a screened lid and inverting the jar on a piece of black filter paper set inside a 62-cm^2 petri dish. The dish was placed inside an incubator set at 27°C and 60% RH. The next day, the eggs laid on the black filter paper were loose and independent from each other. Because of problems with static electricity, we did not pour the eggs directly from the oviposition dish into the treatment dishes. Instead, a batch of 60–70 18–24-h-old eggs was transferred to a small piece of black filter paper by using a camel's-hair brush. We then poured these batches of 60–70 eggs into each randomly chosen treated and untreated concrete arena. The final number of eggs per dish was 50; some of the initial 60–70 eggs were lost during transfer because of handling errors, and the remainder was also removed by using a camel's-hair brush. Randomization for subplot treatments was done by randomly selecting a concrete arena for each exposure period. The treated arenas along with eggs were placed inside a humidity container inside individual temperature incubators, and the untreated controls were held inside the second container. Upon completion of the exposure interval, the eggs were removed and placed on top of sterilized filter paper inside individual, pesticide-free petri dishes, and placed back in the same humidity chambers. Every 8 h, each arena was placed under a dissecting microscope to count the number of emerging larvae. The larvae were usually found within the food media. Eggs in the treatments, including continuous exposure period, were recorded as dead if they had not hatched after 40 d.

Table 1. Equations describing relationship among temperature, exposure interval, and developmental time (top) and relationship among temperature, exposure interval, and mortality (bottom) for Indianmeal moth eggs exposed to hydroprene

Estimate	t	P	Adjusted R^2
Developmental time (d)	0.95		
a	25.4 ± 1.50	16.3	<0.01
b	−0.7 ± 0.14	−6.5	<0.01
c	−0.4 ± 0.03	−1.4	0.04
d	0.01 ± 0.01	2.2	0.20
Mortality (%)	0.70		
a	−19.4 ± 8.6	−1.0	0.30
b	2.1 ± 1.3	1.7	0.01
c	4.7 ± 0.4	1.2	0.02
d	−0.1 ± 0.1	−1.6	0.11

a, intercept; b, temperature; c, exposure interval; d, temperature × exposure interval. All models were computed with df = 4, 121 and are of the form y (developmental time (or) mortality) = $a + b + c + d$.

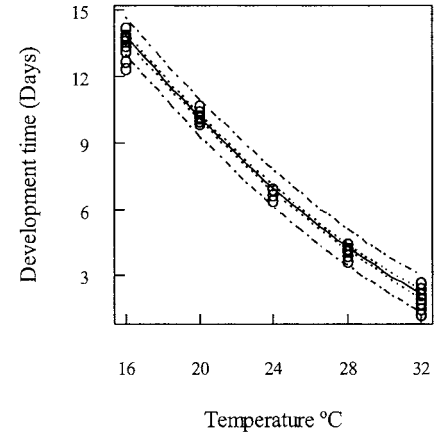

Fig. 1. Duration of development of Indianmeal moth eggs in untreated controls at different temperatures. Fitted regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are the means of three replications at each exposure interval.

Table 2. Equations describing relationships between temperature or exposure interval and developmental time for Indianmeal moth eggs exposed to hydroprene

	Simple linear regression model				Polynomial model					
	$a \pm$ SE	$b \pm$ SE	Adj. R^2	Lack-of-fit P	$a \pm$ SE	$b \pm$ SE	$c \pm$ SE	$d \pm$ SE	Adj. R^2	Lack-of-fit P
Temp (°C)								–		
UTC[a]	24.9 ± 0.3	−0.72 ± 0.01	0.97	<0.01	33.9 ± 1.0	−1.5 ± 0.09	0.01 ± 0.01		0.98	0.05
20	10.4 ± 0.1	0.08 ± 0.01	0.70	0.06				–		
24	7.9 ± 0.1	0.09 ± 0.01	0.81	0.45				–		
28	5.1 ± 0.01	0.12 ± 0.01	0.76	<0.01	4.7 ± 0.2	0.3 ± 0.05	0.01 ± 0.01	–	0.83	0.05
32	3.4 ± 0.01	0.12 ± 0.01	0.70	<0.01	3.0 ± 0.2	0.3 ± 0.05	0.01 ± 0.01	–	0.81	0.39
Exposure (h)								–		
1	24.3 ± 0.6	−0.66 ± 0.02	0.96	<0.01	34.2 ± 2.0	−1.5 ± 0.17	0.02 ± 0.01	–	0.98	0.06
3	24.3 ± 0.6	−0.67 ± 0.02	0.97	<0.01	35.7 ± 1.4	−1.6 ± 0.12	0.02 ± 0.01	–	0.99	0.06
6	23.5 ± 0.4	−0.06 ± 0.02	0.97	<0.01	31.6 ± 1.3	−1.3 ± 0.10	0.01 ± 0.01	–	0.99	0.10
12	12.7 ± 0.5	2.3 ± 0.02	0.97	<0.01	29.9 ± 1.6	−1.2 ± 0.14	0.01 ± 0.01	–	0.90	0.03[b]
18	23.0 ± 0.3	3.0 ± 0.01	0.99	0.01	25.7 ± 1.2	−0.8 ± 0.10	0.01 ± 0.01	–	0.99	0.04[b]
CONT[c]	21.7 ± 0.5	−0.5 ± 0.02	0.95	<0.01	28.1 ± 2.1	−1.0 ± 0.18	0.01 ± 0.01	–	0.96	<0.01

a, b, c, d = $\hat{\beta}_0$, $\hat{\beta}_1$e, $\hat{\beta}_2$e^2, $\hat{\beta}_3$e^3, respectively, for development time models within temperatures and = $\hat{\beta}_0$, $\hat{\beta}_1$t, $\hat{\beta}_2$t^2, $\hat{\beta}_3$t^3, respectively, for developmental time models within exposure intervals. All models are of the form y (developmental time) = $a + bx + cx^2 + dx^3$, *where* x is either temp or exposure interval. All simple linear regression models were computed with df = 1, 23. All polynomial models were computed with df = 2, 22, except for the cubic model for untreated control with df = 2, 72.

[a] Untreated controls (UTC) averaged across all temperatures.

[b] Although the lack-of-fit test for the quadratic models yielded significant results, cubic models that fit the data more closely are less likely to be biologically reasonable for these data.

c For continuous exposure (CONT), eggs were not removed from the treated surface.

Experimental Arenas and Hydroprene Formulation. Hydroprene is registered as an aerosol fog, surface spray, or as an impregnated disc (Arthur 2003). In our study, we evaluated hydroprene as a surface treatment on concrete. We used Rockite (Hartline Products Co., Cleveland, OH; www.Rockite.com) as our treated surface, a special brand of fine-grade ready-mix concrete anchoring material that contains cement but not coarse gravel or dust. The concrete was mixed in an approximate ratio of 3,200 g in 1,600 ml of water to a thick, running consistency (Arthur 1999). The liquid slurry was then poured into individual petri dishes (62 cm^2), to approximately half the capacity of the dish. Ninety dishes were created in this manner, and then they were dried for ≈48 h at room temperature (27°C).

The hydroprene formulation used in the study was made with Gentrol (9.0% [AI], ≈90 mg [AI]/ml). Label directions specify application by mixing 1 oz in 1 gal of water to cover 1,500 feet^2 (29.57 ml in 3.79 liters of water to cover 134.8 m^2), which is 1.9×10^{-3} mg (AI)/cm^2. The area of the concrete petri dish was 62 cm^2, so the volume of spray needed for this area was 0.17 ml. However, this amount was too small to formulate individual concentrations. Therefore, we prepared the hydroprene concentrations by mixing 0.38 ml of Gentrol in 50 ml of distilled water, thoroughly shaking the solution, and removing individual 0.17-ml aliquots for each petri dish. These individual solutions were sprayed on the concrete arenas by using an artist's airbrush (Badger No. 100 LG., Badger Air Brush Co., Franklin Park, IL). The liquid was sprayed by holding the airbrush ≈5–10 cm above the treatment arenas and by slowly releasing pressure until all of the material was dispensed. Twenty-five dishes were treated in this manner. To avoid cannibalism among the emerging larvae after transferring them to new dishes upon completion of required exposure periods, ≈5 ml of standard larval media was provided in each new dish. Eggs on the continuous exposure period were not transferred to new petri dishes but left on the same dish. Therefore, for the five concreted petri dishes that were used for the continuous exposure period, we sprayed by blocking the 1-cm^2 central area of the dish. The food in these petri dishes was put in the center that was blocked while spraying to avoid contamination by hydroprene. These 30 dishes comprised a replicate, and another 30 companion concreted dishes were sprayed with the same volume of distilled water for the untreated control treatment. In subsequent trials, two treated replicates were created as described above, along with an untreated control, for a total of five replications.

Data Analysis. Kramer et al. (1991) showed that erroneous predictions could occur in least square estimations when model parameters are estimated by using some modified form of data, such as rate (1/developmental time). Minimizing the squared error for development rate is not the same as minimizing the squared error for developmental time, especially in the longer developmental time range. Therefore, in this study, we used time instead of rate to fit all our regression models for egg developmental time. The effects of hydroprene on the egg developmental time and mortality were modeled by fitting individual, three-dimensional (3D) response-surface models by using temperature and exposure intervals as predictor variables. These models showed no significant cross-product (or) interaction effect between temperature and exposure period for both developmental time and mortality (Table 1). Such 3D models, especially when they are static and presented in black and white, are difficult to interpret (Merwin et al. 1994) and offer less quantitative information to a scientific reader than

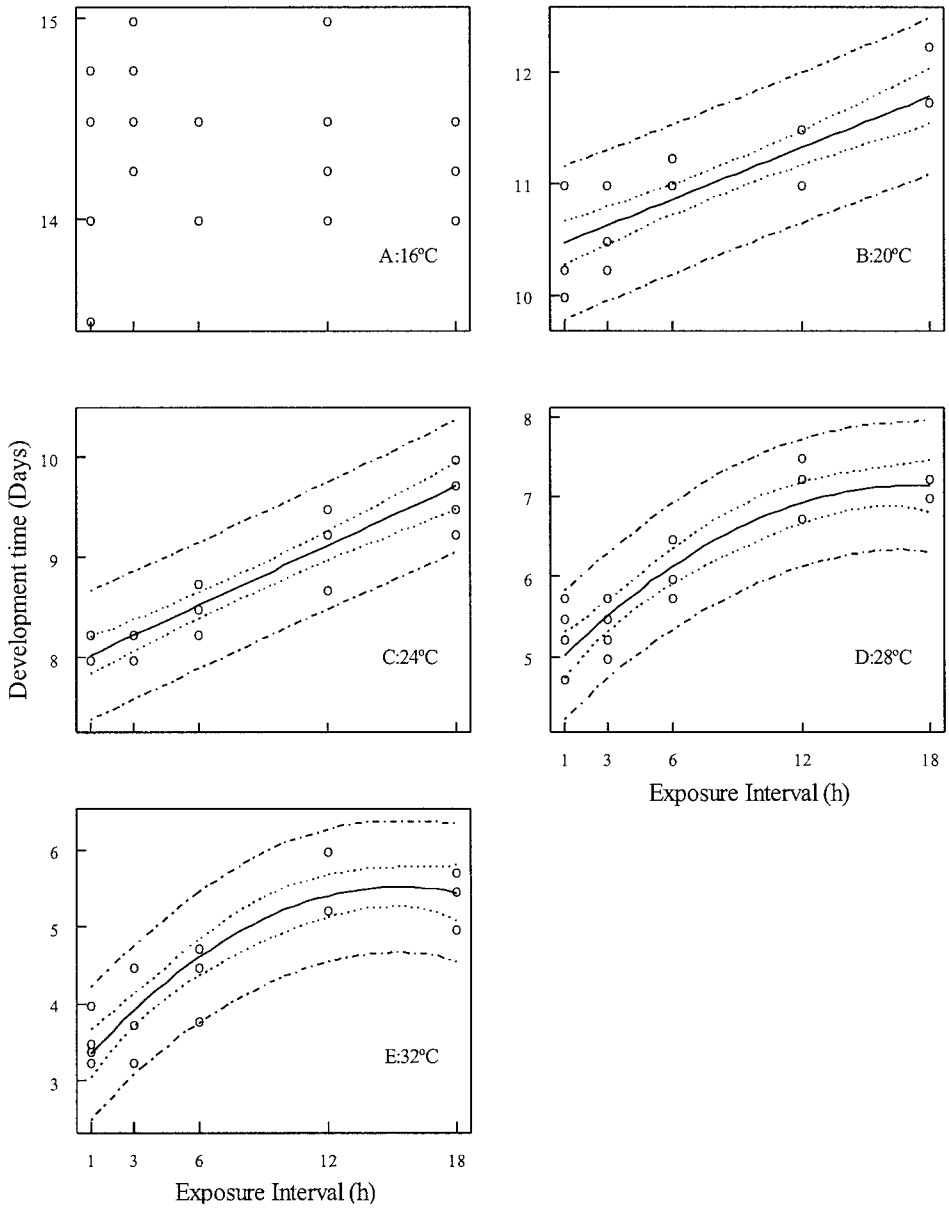

Fig. 2. Duration of development of Indianmeal moth eggs when exposed to hydroprene at various temperatures for different exposure periods. Fitted regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

two-dimensional graphs. Therefore, for our data, two kinds of plots showing comparisons for mortality and developmental time were plotted; the effect of exposure interval within a given temperature, and the effect of temperature within a given exposure interval. The developmental and mortality effects from continuous exposure treatment were analyzed separately from the remaining exposure treatments. Simple linear and polynomial model fitting were done using the Linear Modeling procedure (Chambers 1992) in S-Plus (version 5.1 for Sun SPARC, SunOS 5.5, Insightful Corporation, Seattle, WA).

The regression models for developmental time and mortality were chosen based upon lack-of-fit-tests, but not R^2 or adjusted R^2 values, which are traditionally considered to be standards for model selection. Because this is a designed experiment and the observations are derived from replicated units, it was possible to conduct lack-of-fit tests by partitioning the residual sum of squares into lack of fit and pure error components (Weisberg 1985). This involved determining the part of the residual sum of squares that can be predicted by including additional terms for the predictor variables in the model, like higher order polynomial

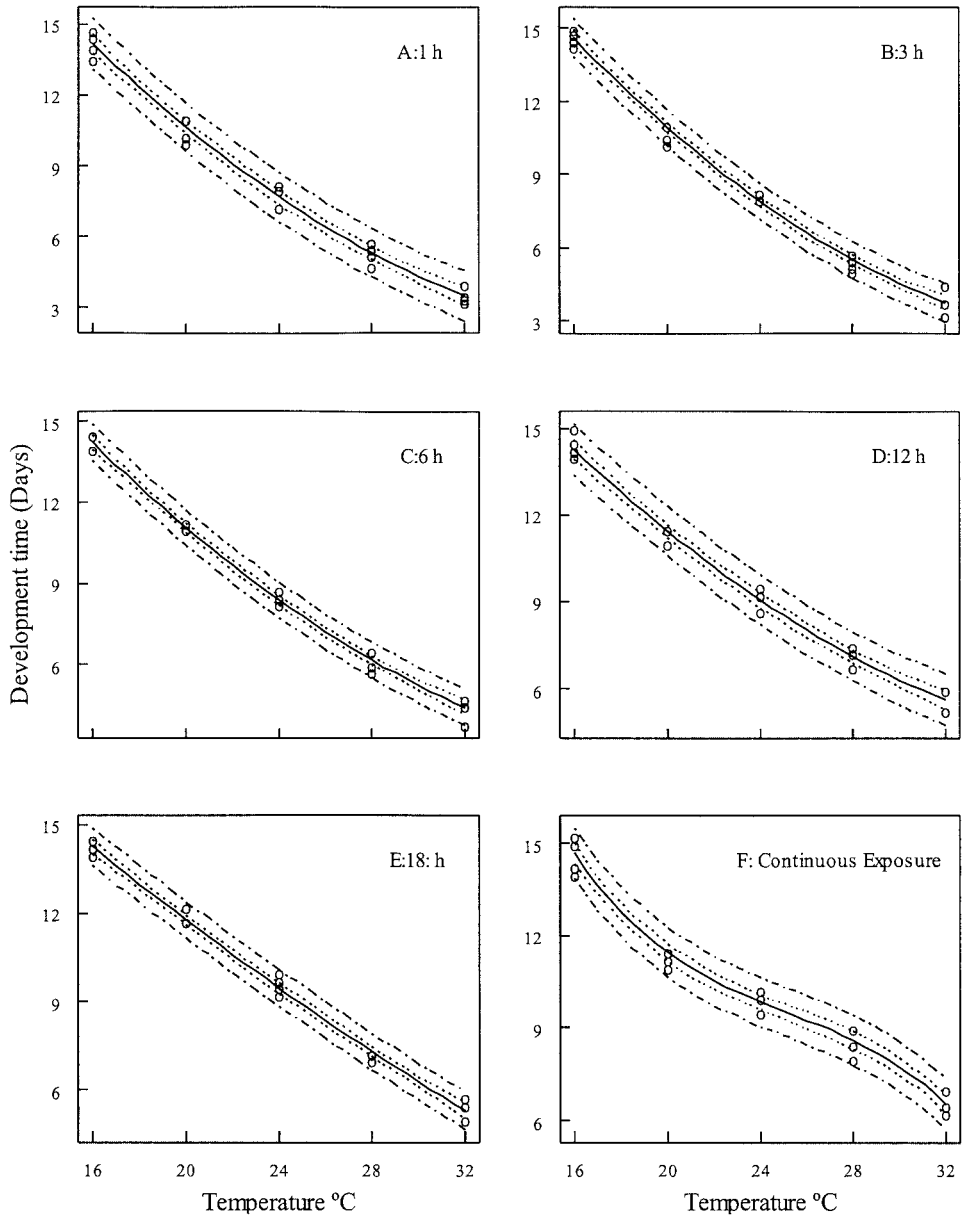

Fig. 3. Duration of development of Indianmeal moth eggs when exposed for various exposure periods in different temperatures or (F) when exposed continuously on treated surfaces at different temperatures. Fitted regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

terms, and the part of the residual sum of squares that cannot be predicted by any additional terms, i.e., the sum of squares for pure error. A test of lack-of-fit for the model without the additional terms was then performed, by using the mean square pure error as the error term. This provided a sensitive test of model fit because the effects of the additional higher order terms were removed from the error. Care was taken to fit models that not only described the data adequately but also that were more biologically reasonable (Throne 1994, Faraway 1999).

Thus, we selected appropriate models for individual data sets by computing comparisons made between the desired and saturated models with higher order polynomial terms by the way of F-testing methodology (Faraway 1999). Influential observations in the data set were checked for by using Cooks distance plots. Nonconstant variance (heteroscedascity) and nonlinearity were checked by plotting residuals for the selected models (Faraway 1994). The strengths of the regression relationships were measured by their adjusted R^2 values (Seber 1977), and 95% confidence

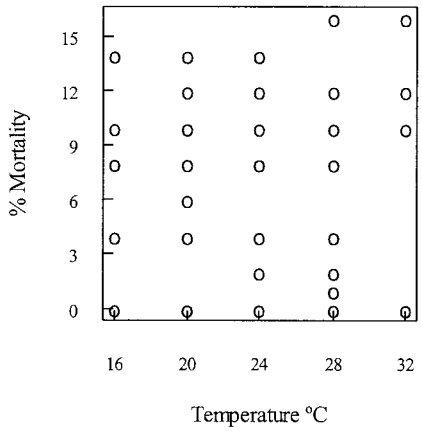

Fig. 4. Percentage of mortality of Indianmeal moth eggs in untreated control at various temperatures. Open circles indicate the mean of three replications at each exposure interval.

intervals on the mean and prediction intervals were plotted for individual equations (Becker et al. 1988, Murrell 1999).

Results

Developmental Time. The number of days required for eggs to hatch in the untreated controls and in the treatments generally decreased as the temperature increased (Figs. 1 and 3; Table 2). Maximum developmental time in the untreated controls was 13.6 ± 0.6 d at 16°C, and minimum developmental time was 2.3 ± 0.4 d at 32°C. At 16°C, there was no relationship between egg developmental time and exposure interval ($F = 0.87$; df = 1, 23; $P = 0.35$) (Fig. 2A), and the average developmental time was 14.3 ± 0.3 d. At 20 and 24°C, the effect of hydroprene on egg development became more evident; developmental time generally increased with exposure interval, with some variability in the data (Fig . 2B and C). Linear models fit the data at 20 and 24°C (Table 2). The developmental time increased at 28 and 32°C as exposure intervals increased; however, this increase was more gradual than at the lower temperatures and tended to level off at the highest exposure intervals (Fig. 2D and E). Thus, quadratic models were fit to the data (Table 2).

At each exposure interval, the developmental time decreased as the temperature increased (Fig. 3; Table 2). At 1, 3, and 6 h, the developmental time ranged from 3 to 15 d, and quadratic models were fit to the data (Fig. 3A–C, respectively). At 12- and 18-h exposures and continuous exposure, developmental time ranged from 5 to 15 d, but the effects of temperature were more gradual, and quadratic models fit the data (Fig. 3D–F; Table 2). (A cubic model is actually fit to the continuous exposure data.)

Mortality. There was no significant relationship between egg mortality and temperature in the untreated controls ($F = 2.95$; df = 1, 73; $P = 0.08$) (Fig. 4). The mean mortality among all temperatures was 7.3 ± 4.6%. Among the treatments, mortality of eggs increased as the exposure periods increased within any given temperature (Fig. 5A–E; Table 3). The mortality was lowest at 16°C when exposed for 1 h (0 ± 3%), but mortality gradually increased as the exposure interval increased. A quadratic model was fit to the data at 16 and 20°C. Linear equations were fit to the data for 24, 28, and 32°C.

Within each exposure interval, there was an increase in mortality as the temperature increased (Fig. 6A–E). Quadratic regressions were fit to the data at 1, 3, 6, and 12 h (Table 3). At the 18-h exposure interval, there was a sharper increase in mortality with each successive increase in temperature, to a maximum of 78 ± 7.5% at 32°C (mean is not 78 in Fig. 5 or 6) (Fig. 6E), and the data were described by a linear equation. When the eggs were continuously exposed to hydroprene, mortality also increased with increase in temperature (Fig. 6F). A cubic model fit the data.

Discussion

The lower development threshold temperature for two strains of Indianmeal moth eggs, one wild-type strain and one laboratory-reared strain, were reported as 14.8°C (Johnson et al. 1995). Indianmeal moths reared below 14.8°C diapause in the pupal stage. Therefore, the lowest temperature used in our study was 16°C to avoid inducing diapause. Hydroprene did not have a significant effect on the developmental time of eggs at 16°C; however, hydroprene caused significant mortality (up to 32 ± 3%) at this temperature. As the temperature increased, there was a steady increase in the delaying effect of hydroprene, suggestive of increased hydroprene activity at increasing temperatures above 16°C. Low volatility, binding to the concrete surface, and/or low penetration rate across the eggshell at low temperatures could have contributed to less developmental effect and mortality at 16°C. The results suggest that hydroprene is most effective against the eggs of Indianmeal moth at temperatures >20°C.

Bhargava and Urs (1993) reported mortality effects on the eggs of rice moth exposed to various doses of hydroprene and other growth regulators. Among the three age groups of eggs that they exposed to hydroprene, the hatching percentage was highly reduced in the freshly laid eggs (0–12 h old) compared with older eggs. Their tests were conducted on eggs that were kept on laboratory media. In the USA, hydroprene is not labeled for direct use on stored food, and, therefore, there is less chance for the eggs that are developing inside the food material to contact hydroprene, unless hydroprene is applied as an aerosol fog. The results described by Bhargava and Urs (1993) might not be directly applicable to storage conditions in the USA.

Under storage conditions used in the USA, it is possible that eggs may be laid on surfaces treated with hydroprene. Adult Indianmeal moths lay their eggs on the food or in the vicinity of food sources. Mullen and

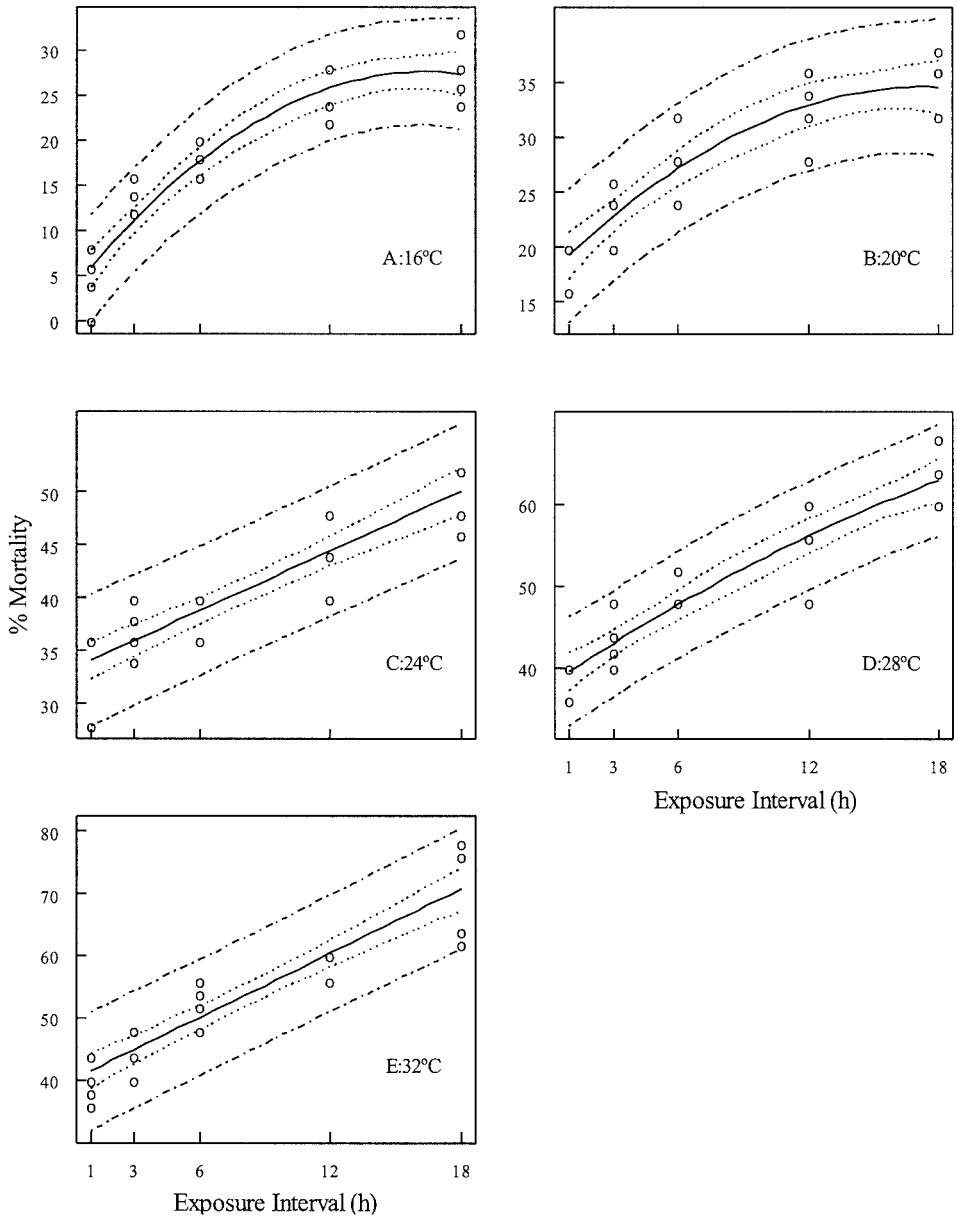

Fig. 5. Percentage of mortality of Indianmeal moth eggs when exposed to hydroprene at various temperatures for different exposure periods. Fitted regression model (solid line), 95% confidence intervals at mean (dotted line), and prediction intervals (dashed line). Open circles are independent observations from five replications.

Arbogast (1977) showed that oviposition was stimulated by the presence of food materials in two stored-product moths, Indianmeal moth and the almond moth. More recent studies described the oviposition behavior of Indianmeal moth by conducting choice tests of egg laying preferences of female moths on various food media (Mbata 1990, Phillips and Strand 1994, Nansen and Phillips 2003). Phillips and Strand (1994) found that female Indianmeal moths orient toward food odor and lay more eggs on dishes containing food media and those contaminated with larval secretions. The proportion of eggs laid on nonfood surfaces, when food was inaccessible, is not evident from these studies. Recently, in a study conducted under a simulated warehouse set up with controlled environmental conditions, adult Indianmeal moths walked on the warehouse floors and laid their eggs on the surfaces or inside containers provided with different stored-product commodities (Silhacek et al. 2003). In that study, fewer eggs were laid directly on commodities and more were laid on the surfaces of containers. In a simulated food product environment,

Table 3. Equations describing relationships between temperature or exposure interval and mortality for Indianmeal moth eggs exposed to hydroprene

	Simple linear model				Polynomial model					
	$a \pm$ SE	$b \pm$ SE	Adj. R^2	Lack-of-fit P	$a \pm$ SE	$b \pm$ SE	$c \pm$ SE	$d \pm$ SE	Adj. R^2	Lack-of-fit P
Temp. (°C)								–		
16	7.4 ± 1.22	1.3 ± 0.1	0.81	<0.01	2.8 ± 1.3	3.0 ± 0.4	−0.09 ± 0.02	–	0.90	0.08
20	20.2 ± 1.029	0.9 ± 0.1	0.76	0.03	17.3 ± 1.3	2.0 ± 0.4	−0.06 ± 0.02	–	0.82	0.44
24	33.1 ± 0.94	0.9 ± 0.1	0.80	0.57				–		
28	38.8 ± 0.99	1.4 ± 1.0	0.89	0.55				–		
32	39.8 ± 1.43	1.7 ± 0.1	0.85	0.36				–		
Exposure (h)								–		
1	28.6 ± 4.53	2.3 ± 0.2	0.86	<0.01	−110.2 ± 13.1	9.5 ± 1.1	−0.15 ± 0.02	–	0.95	0.30
3	16.8 ± 3.66	2.0 ± 0.1	0.88	<0.01	−78.0 ± 11.9	7.4 ± 1.0	−0.11 ± 0.02	–	0.94	0.13
6	18.6 ± 2.71	2.3 ± 0.1	0.94	<0.01	−53.6 ± 10.8	5.4 ± 0.9	−0.06 ± 0.02	–	0.96	0.11
12	12.7 ± 3.2	2.3 ± 0.12	0.93	0.03	−40.9 ± 14.2	4.0 ± 1.3	−0.03 ± 0.03	–	0.93	0.07
18	22.9 ± 3.9	3.0 ± 0.15	0.93	0.06	7.0 ± 13.1	1.8 ± 1.1	−0.04 ± 0.02	–	0.97	<0.01
CONT[a]	−20.2 ± 2.9	3.2 ± 0.12	0.96	<0.01	263.3 ± 57.6	33.7 ± 7.6	1.54 ± 0.32	−0.01 ± 0.0	0.98	0.08

$a, b, c, d = \hat{\beta}_0, \hat{\beta}_1 e, \hat{\beta}_2 e^2, \hat{\beta}_3 e^3$, respectively, for mortality models within individual temperatures and $\hat{\beta}_0, \hat{\beta}_1 t, \hat{\beta}_2 t^2, \hat{\beta}_3 t^3$, respectively, for mortality models within individual exposure intervals. All models are of the form y (mortality) $= a + bx + cx^2 + dx^3$, *where* x is either temperature or exposure interval. All simple linear models were computed with df = 1, 23, and all polynomial models with df = 2, 22, except for the cubic model for continuous exposure with df = 3, 21.

[a] For continuous exposure (CONT), eggs were not removed from the treated surfaces.

when eggs of the three species of stored-products pests, the red flour beetle *Tribolium castaneum* (Herbst), the confused flour beetle *Tribolium confusum* Jacquelin du Val, and the almond moth were placed in open and closed food media and hydroprene was applied as a surface spray, the insects showed lengthened larval development and sterility in adults (Bell and Edwards 1999). In the absence of food or when the food is inaccessible because of packaging or because of other barriers, the female Indianmeal moths may lay their eggs within the vicinity of food sources so emerging larvae can crawl toward the commodity. Therefore, it is possible for eggs to contact surfaces sprayed with hydroprene, although the actual proportion is not known.

Insect resistance to juvenile hormone analogs was once thought to be impossible (Williams 1967). Today, reports of resistance to compounds that are similar to hydroprene are not uncommon. Mosquito resistance to methoprene is widely known (Dame et al. 1998; Cornel et al. 2000, 2002). Cornel et al. (2002) reported a several 1000-fold increase in LC_{50} and LC_{90} tolerance levels for the Fresno strain of the mosquito, *Ochlerotatus nigromaculis* (Ludlow), and control strategies involving methoprene were discontinued to prevent further resistance development. Whitefly species have developed resistance to pyriproxifen, another insect growth regulator (IGR) (Horowitz and Ishaaya 1994, Horowitz et al. 2002). One possible method to delay the development of resistance by Indianmeal moth toward hydroprene is by timing to target the application toward the vulnerable life stages of Indianmeal moth, including the egg stage. Regression models derived in this study will be incorporated into a computer simulation model that can be used for timing hydroprene application.

The results of this study show that hydroprene can be used to control the egg stage of Indianmeal moth when applied as a surface treatment. Other IGRs also may possess similar properties and should be tested for Indianmeal moth management as well. Reid and Bennet (1994) showed that hydroprene has the potential to affect long-term population growth of German cockroaches, *Blattella germanica* (L.); populations treated with hydroprene decline over time. Similar studies on the populations of stored-product pests, including that of Indianmeal moth, would help in proper use of hydroprene in food handling environments that are sensitive to chemical applications, like packaging and retail facilities. Simulation models can be used to predict pest occurrence, timing of management strategies, and to evaluate a management strategy such as hydroprene application. Models for development and mortality derived from this study can be incorporated into a simulation model for the population dynamics of Indianmeal moth to optimize management strategies.

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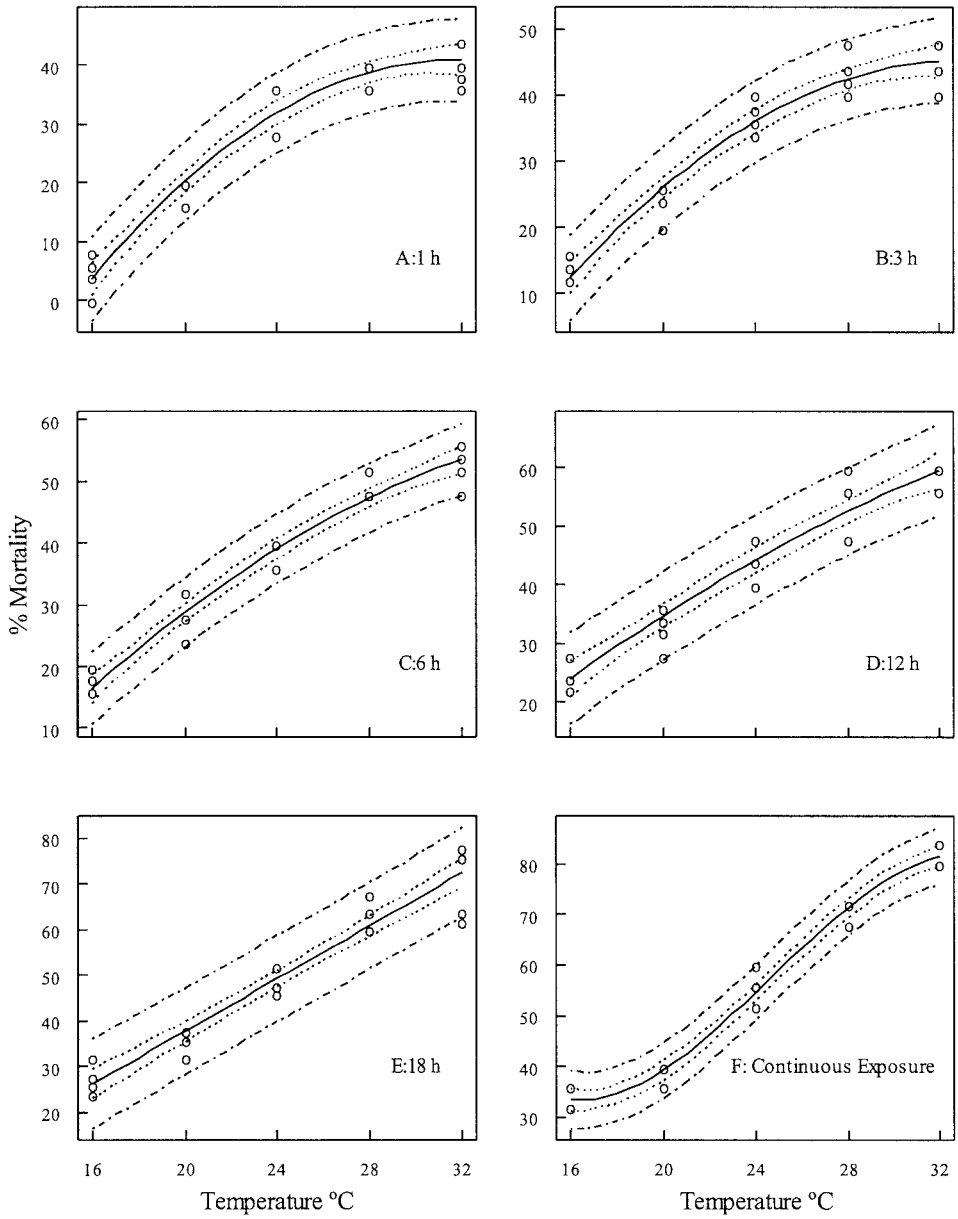

Fig. 6. Percentage of mortality of Indianmeal moth eggs exposed to hydroprene for different exposure intervals at different temperatures or (F) when exposed continuously on the treated surface at different temperatures. Fitted regression model (solid line) and 95% confidence intervals at mean (dotted line) and prediction intervals. Open circles are independent observations from five replications.

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